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Mass limits for fourth generation sequential neutrinos from dark matter experiments

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Abstract

Current mass limits for fourth generation sequential neutrinos come from dark matter experiments assuming $\rho_{DM} = 0.2 - 0.8$ g/ cm^3. We show that the latest results from the CDMS II experiment exclude Dirac neutrinos with masses below 500 GeV assuming only that they are produced as expected by the Big Bang model and clump in the same manner as baryons. We also show the next generation of nuclear recoil experiments will be sensitive to fourth generation Majorana nuetrinos. Finally, we consider the case in which the neutrino interacts with the nucleus via the exchange of a Higgs boson.

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I. INTRODUCTION

Although not fashionable, experimental and theoretical considerations do not exclude a fourth lepton generation. Accelerator searches exclude a variety charged heavy leptons up to about 100 GeV [1]. All neutrinos with masses less than $M_Z/2$ are excluded by the Z^o lineshape [1] and stable neutrinos with masses less that 100 GeV are excluded assuming Dirac couplings to e, μ or τ.

In the early 1990's, neutrinos with masses in the range of 10-1000 GeV were a prime dark matter candidate [2, 3, 4]. The earliest dark matter and solar capture measurements excluded neutrinos as the predominant source of dark matter assuming they had a local density of $\rho \sim 0.4 \mathrm{GeV/cm^3}$, i.e. *were* the dark matter expected in our galaxy. Since then, supersymmetric models, most notably those with neutralinos in the 100 GeV mass range, have taken over as the prime massive dark matter candidate [5, 6].

In the intervening time, several things have happened: 1) measurements have shown the three lightest neutrinos are massive and mix [7], 2) advances in cosmology have led to a much clearer understanding of the early universe [8]and 3) subsequent nuclear recoil experiments have achieved 10^7 greater sensitivity than the first experiments [9].

In this note, we return the the question of fourth generation sequential neutrinos as a relics of the Big Bang and use recent experimental results to place limits on the mass of both Majorana and Dirac neutrinos without the assumption they are the main constituent of the galactic dark matter. We take their calculated density from the Big Bang and assume they fall into galaxies in the same manner as baryons. We assume the fourth generation neutrino, N, is stable on the time scale of the universe, which means it does not mix much with lighter species and that its partner lepton L is heavier, $m_L > m_N$.

Our note is organized as follows: in the next section, we summarize the production of fourth generation stable neutrinos in the Big Bang. In the following section, we compute the recoil interaction rate and extract limits from the current underground detectors for both Majorana and Dirac neutrinos. In the final section, we conclude and discuss the limits from neutrino capture and cosmic ray experiments.

II. NEUTRINO PRODUCTION IN THE BIG BANG

Very early in the Big Bang, when $T > 10^{10}$K, the fourth generation neutrinos with masses around 100 GeV would be in equilibrium with the light charged leptons via annihilation. However, as originally discussed in [10], at about 10^{10} K, the neutrinos become sufficiently dilute that the annihilation rate becomes small in comparison with the dilution from the expansion of the universe. Numerical solution to the rate equation gives a present day average cosmological number density $n_o = 10^{-4}(GeV^2/cm^3)m_\nu^{-2}$ [11].

Like baryonic and dark matter, the neutrinos will concentrate in galaxies with a typical velocity of 250 km/s. Assuming neutrinos clump in galaxies the same way baryonic matter does, this gives an estimate for galactic neutrino density of $n_G = (r_G/r_D)^3 n_0$, where r_G is the size of the galaxy, and r_D is the distance scale between galaxies. Using 10 kpc for r_G and 1 Mpc for r_D gives $n_G = 10^6 n_0$. This estimate is good to a factor of 4, so we can place an upper limit of $2 \times 10^6 n_0$ on the local heavy neutrino density from the Big Bang [6].

III. NUCLEAR RECOIL DETECTION

The spin-independent cross section for Dirac neutrinos scattering coherently from a nucleus via neutral current:

$$\begin{aligned} \frac{d\sigma}{dT} &= \frac{G_F^2 m_N c^2}{8\pi v^2}[Z(1-4sin^2\theta_W)-N]^2 \\ &\times\ [1+(1-(\frac{T}{E_\nu})^2)-\frac{m_N T + m_\nu^2}{E_\nu^2}] \\ &\times\ \exp(-m_N 2TR^2/3\hbar^2) \end{aligned}$$

where T is the recoil energy, m_N is the mass of the nucleus, v is the velocity of the neutrino, R=1.2fm$A^{\frac{1}{3}}$, and $A = N + Z$. The exponential term models the loss of coherence: the cross section is down by a factor of $1/e$ when $T = 3\hbar^2/2m_N R^2 \sim 50\mathrm{Me}V/A^{5/3}$. for most target materials, this gives $T \sim 50$ keV. Similarly, the cross section for the elastic scattering of Majorana neutrinos is

$$\frac{d\sigma}{dT} = \frac{G_F^2 m_N c^2}{\pi v^2}C^2\lambda^2 J(J+1) \tag{1}$$

where $\lambda^2 C^2 J(J+1)$ is related to the quark spin content of the nucleon, and the nucleon spin content of the nucleus [12] Values for $\lambda^2 C^2 J(J+1)$ can be found in Table I. Fig. 1 shows

cross sections of neutrinos of varying mass for different estimates. The neutrinos may also exchange a Higgs boson with the nucleus

$$\frac{d\sigma}{dT} = \frac{G_F^2 m_N c^2}{8\pi v^2} \frac{m_\nu^2 m_N^2}{m_H^4} \left(1 + (1 - (\frac{T}{E_\nu})^2) - \frac{m_N T + m_\nu^2}{E_\nu^2}\right) \exp\left(-\frac{m_N 2 T R^2}{3\hbar^2}\right) \tag{2}$$

where m_H is the yet unknown Higgs mass. Higgs exchange cross section will be the same regardless of whether the neutrino is Dirac, Majorana, or sterile.

The rate of events seen in the detector over an recoil energy range ΔT is then

$$R = \Delta T \frac{m_T}{m_N} \frac{\rho_\nu}{m_\nu} \int_{v_{min}}^{v_{max}} \frac{d\sigma}{dT} f(v) v d^3v \tag{3}$$

where m_T is the target mass, ρ_ν is the local neutrino density, and $f(v)$ is the Maxwell Boltzmann distribution of neutrino velocities. We use $\overline{v} = 270$ km/s for the average velocity of the Earth relative to the dark matter halo. Since the recoil spectrum always falls with increasing recoil energy, the most sensitive bin is the lowest bin above threshold. Thus, with an upper limit on the number of events seen in the lowest bin, an upper limit on the local neutrino density can be obtained, which gives a limit on the cosmological density n_o. If the value of n_o predicted for a relic neutrino of mass m_N is larger than derived from the count rate in the lowest bin in the recoil spectrum, then neutrinos of that mass cannot exist.

The CDMS II experiment [9] observed no counts in the energy range above T=20 keV with an energy resolution of ΔT=1.5 keV over an exposure time of 19.4 kg-days. The actual experimental threshold is 10 keV, but for our purposes the best limit is given by taking 20 keV, where the efficiency is much higher. The 90% confidence limit on no counts is $N_{90} = 2.3$, so the limit is:

$$\rho_\nu < \frac{N_{90}}{m_T/(m_N m_\nu) \tau \Delta T \int_{v_{min}}^{v_{max}} d\sigma/dT f(v) v d^3v} \tag{4}$$

The 90% confidence limits on relic neutrino density are plotted in Fig. 3(a) for Dirac neutrinos, Fig. 3(b) for Majorana neutrinos, and Fig. 3(c) for neutrinos whose interactions are dominated by Higgs exchange. From Fig. 3(a), it is apparent that the CDMS II data in combination with the expected density of relic neutrinos from the big bang allows us to put a lower limit on the mass of a possible heavy Dirac neutrino of about 500 GeV. If we assume a density of 0.4 g/cm^3, the limit increases to 3 TeV. Fig. 3(b) and (c) show that current results do not exclude any of the mass range above $M_Z/2$ for Majorana neutrinos. However, the next generation of nuclear recoil experiments will be a factor of 10-100 more sensitive

TABLE I: Spin content factor values obtained from Ref. [12].

Experiment	$C^2\lambda^2 J(J+1)$
NQM	0.0260 ± 0.0013
EMC 1	0.0221 ± 0.0020
EMC 2	0.0169 ± 0.0046

providing access to Majorana masses in the range of 100 GeV. Additionally, if the Higgs mass is found to be around 110 GeV, the dependence on neutrino mass in the Higgs cross section would allow a detector with 100 times the exposure of the CDMS experiment and a null result to completely rule out the existence of heavy neutrinos of all masses. Conversely, if heavy neutrinos were known to exist, a null result from such a detector could place limits on the Higgs mass.

IV. CONCLUSION

Our results assume the neutrino's density traces the density of the baryons. This in fact may not be true: recent numerical simulations indicate the dark matter distribution may be rather non-uniform with density variations as high as a factor of thirty [13], reducing our limit to roughly 100 GeV for Dirac neutrinos. Since the Earth may be located in a less dense region, there is still a loophole for massive neutrinos. However, searches for the decay products of dark matter annihilation in cosmic rays [14] probe the local ∼3 kpc of our galaxy and solar capture [15] signals are proportional to the average relic neutrino density over a substantial fraction of the galaxies history. Both of these measurement may help close the loophole.

Acknowledgments

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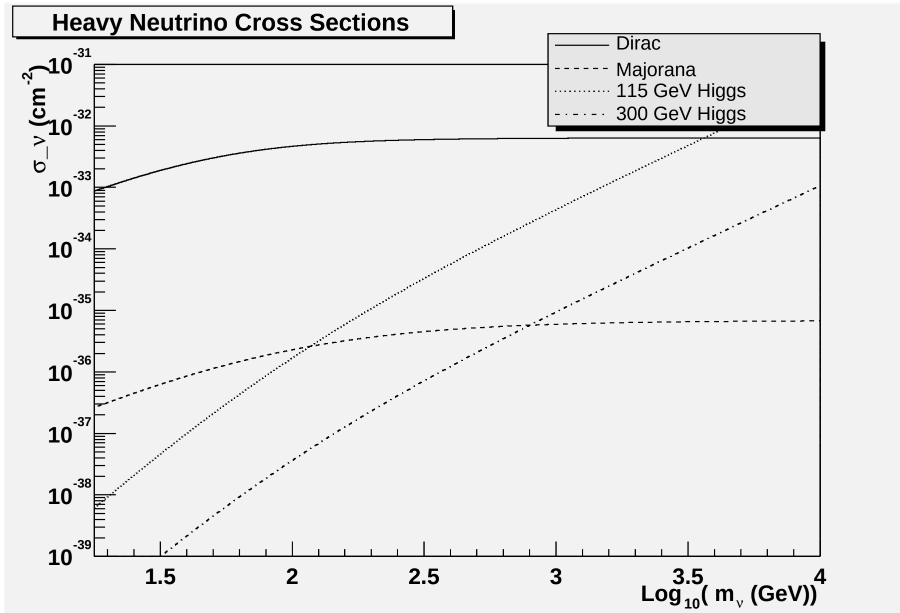

FIG. 1: Total Neutrino Cross Sections for Spin Dependent, Spin Independent, and Higgs Interactions

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[1] K. Hagiwara et al., Physical Review D **66**, 010001 (2002).

[2] S. Ahlen et al., Phys. Lett. B **195**, 603 (1987).

[3] M. T. et al., J. Phys. G: Nucl. Part. **17**, S193 (1991).

[4] D. Caldwell et al., Phys. Rev. Lett **61**, 510 (1988).

[5] J. Ellis et al., Phys. Lett. B **245**, 251 (1990).

[6] G. Jungman, M. Kamionkowski, and K. Griest, Phys. Rep. **267**, 195 (1996).

[7] P. Fisher, B. Kayser, and K. McFarland, Ann. Rev. Nucl. part. Sci. **49**, 481 (1999).

[8] W. Freedman and M. Turner, Rev. Mod. Phys. **75**, 1433 (2003).

[9] D. Akerib et al., astro-ph/0405033 (2004).

[10] S. Weinberg and B. Lee, Phys. Rev. Lett. **39**, 165 (1977).

[11] G. Boerner, The Early Universe (2003).

[12] J. Lewin and P. Smith, Astroparticle Physics **6**, 87 (1996).

[13] C.-P. Ma and E. Bertschinger (2003), astro-ph/0311049.

[14] A. Malinin, Phys. Atom. Nucl. p. 67 (2004).

[15] S. Desai et al., Phys. Rev. D p. 083523 (2004).

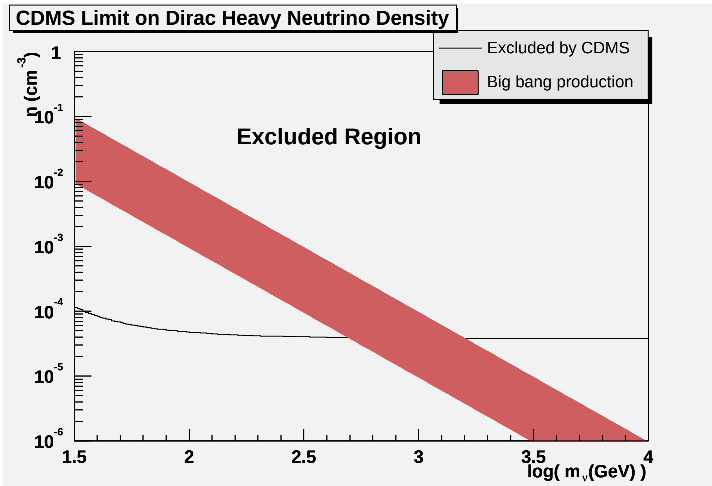

FIG. 2: Limits on Neutrino Density for Dirac Neutrinos

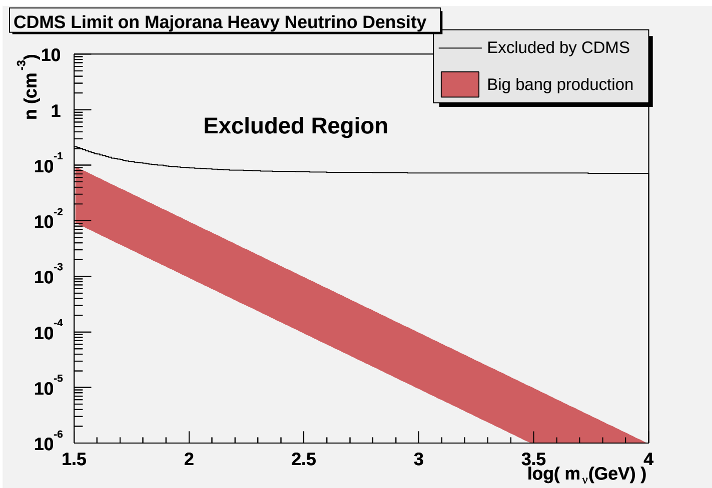

FIG. 3: Limits on Neutrino Density for Majorana Neutrinos

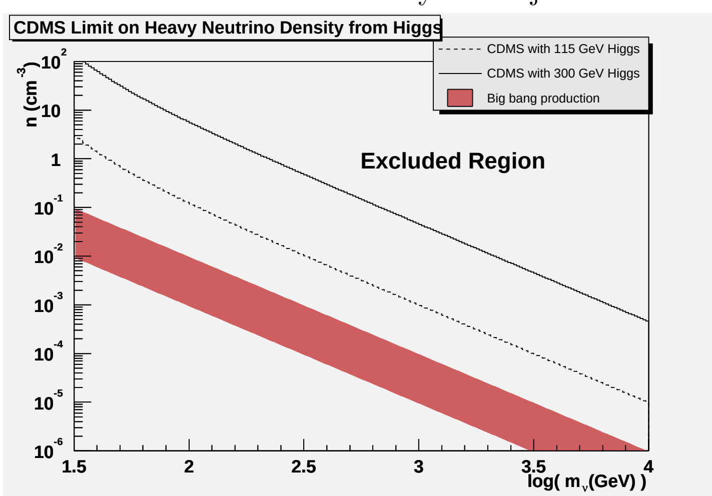

FIG. 4: Limits on Neutrino Density from Higgs interaction, for Higgs masses of 115GeV and 300 GeV